

16/P&T

- 1 -

GAS FLOW MEASURING APPARATUS AND SIGNAL PROCESSING
METHODS APPLICABLE THERETO

Field of the Invention

5 The present invention relates generally to gas flowmeters containing one or more differential pressure transducers measuring pressure drop across a flow-resistive element placed inside the gas passageway. More particularly, the present invention relates to improvement in the accuracy of flowmeters used in spirometry, by special design of the gas passageway, 10 by increasing its immunity to vibrations and by providing special signal processing and a linearization method applicable to a flowmeter or other like transducer signals.

Background

15 Typically, a gas flowmeter contains a gas flow receiver (GFR) (also called gas passageway), a tube through which gas flow passes, and a differential pressure transducer thus connected to the GFR. The transducer measures differential pressure generated by a flow-resistive element placed inside the tube. For certain applications, such as spirometry, GFRs 20 having simple shape, providing easy cleaning and/or disposability, are the most attractive. Among GFRs used in industry and medicine, one can find tubes with flow-resistive elements made in the form of plane diaphragms (flow-obstacles designed to create local differential pressure while allowing flow). The closest prototype used in spirometry, is the GFR with crest-like 25 flow-resistive element [US Patent 5038773].

30 The particular design of the GFR used in spirometry is the result of a trade-off between the imperative to increase differential pressure generated by the flow-resistive element to obtain higher sensitivity of the flowmeter, and the requirement not to exceed a maximum acceptable back-pressure specified by spirometry standards. For example, the American Thoracic Society Standards for Spirometry (1994) require the back-pressure to be

not greater than 150 Pa·s/l in the whole operating range. Therefore a GFR with highest ratio (differential pressure)/(back pressure) is preferable for this particular application.

Another problem to be solved in the described flowmeter is related 5 to reproducibility of the transformation characteristic of the GFR, which defines flow-to-differential-pressure conversion. For this purpose, simpler shapes of the GFR are easier to manufacture, with better reproducibility of the dimensions of the inner features and surface of the tube, which eventually guarantee reproducibility of the conversion. Another result of the 10 tube shape simplification is the reduction of manufacturing costs, which is of great importance, especially for disposable tubes.

It has been shown [US Patent 5038773] that GFRs with flow- 15 resistive elements made in the form of plane diaphragms have essentially non-linear flow-to-differential-pressure conversion characteristics. Typically, the differential pressure which is generated by this type of GFR is close to a square function of the flow, which results in the following problem. A requirement to measure flow in a dynamic range of 10^3 , say from 15ml/s to 15l/s (spirometry), necessitates the measurement of differential pressure, generated by the GFR, in a dynamic range of $10^6 = (10^3)^2$. On the other 20 hand, a limitation of maximal flow impedance of the GFR at about 150Pa·s/l, established by contemporary spirometry standards (American Thoracic Society Standards for Spirometry), restricts the maximal generated back-pressure to $(150\text{Pa}\cdot\text{s/l}) \times (15\text{l/s}) \approx 2\text{kPa}$. Therefore the minimum detectable differential pressure of the pressure transducer should 25 be at the level of a few mPa. This requirement, combined with the necessity to operate in a dynamic range of six orders of magnitude, is a serious challenge for differential pressure transducers. Medical Graphics Corp. proposed a flowmeter containing two differential pressure sensors with an overlapping operating range of six orders of magnitude having a 30 special sensor activated at low flows [US Patent 5038773]. The electronic

- 3 -

module of this spirometer has a sophisticated structure and contains sub-modules providing analog signal conversion before being digitized by an analog-to-digital converter (ADC).

Usage of thermoanemometer-type transducers connected in parallel

5 to the GFR for flow measurements has been reported earlier [U.Bonne, K.Fritsch, "Mikroanemometer für die Durchflußmessung von Gasen," Technisches Messen, 1994, v.61, n.7, pp.285-294; T.R.Ohnstein, R.G.Johnson, R.E.Higashi, D.W.Burns, J.O.Holmen, E.A.Satren, G.M.Johnson, R.E.Bicking, S.D.Johnson, "Environmentally Rugged, Wide

10 Dynamic Range Microstructure Airflow Sensor," Proceedings on Solid-State Sensors and Actuators Conference (1990), pp.158-160]. One particular thermoanemometer-type transducer has a linear operating range of about four orders of magnitude and total operating range of more than six orders of magnitude [Frolov G.A., Gendin A.V., Grudin O.M., Katsan I.I.,

15 Krivoblotskiy S.N., Lupina B.I., "Micromechanical thermal sensors for gas parameters measurements," Proceedings of 1996 ASME International Engineering Congress and Exposition, DSC-Vol.59, Micro-electro-mechanical systems, pp. 61-65]. This particular transducer covers the whole operating range that makes it attractive for usage in flowmeters.

20 Another advantage of thermoanemometer-type sensors is that their resolution can be improved to a level as fine as several mPa without degrading their dynamic properties. For example, the response time of the mass flow AWM-series sensors manufactured by Honeywell Inc., with resolution mentioned above, is about 3ms.

25 A thermoanemometer-type transducer contains a functional element sensitive to gas flow passing through a specially designed gas flow assembly [US Patent 4548078]. This gas flow is proportional to pressure drop across the transducer, which makes it also possible to use it also for differential pressure measurements. The physical principle of gas flow

30 measurement is based on flow-induced disturbance of a symmetrical temperature distribution in the gas around a heater. This disturbance,

caused by the shift of the heated volume of gas in the direction of flow, is usually detected by a pair of temperature-sensitive elements. Typically, the flow-sensitive element contains one or two heaters, which warm the gas in a certain region of the flow channel. It also includes at least two 5 temperature-sensitive elements detecting distortion of the temperature distribution in the heated volume of gas. The functions of gas heating and temperature sensing can be separated, for example, as in the sensor with the central heater and two temperature-sensing elements on opposite sides of the heater [US Patent 4548078]. In an other design, the flow sensor may 10 use only two self-heated temperature-sensing elements, which warm the gas and measure the temperature difference simultaneously [H-E. de Bree, P. Leussink, T. Korthorst, H. Jansen, T S J. Lammerink, M. Elwenspoek, "The μ -flow: A novel device for measuring acoustic flows," Sensors and Actuators A (1996), v.54, n.1, pp.552-557]. The differences between such 15 designs are not sufficient for subsequent consideration in this document.

Thermoanemometer-type flow or differential pressure transducers are sensitive to acceleration acting in the direction parallel to the gas flow in the transducer flow channel. This effect, caused by the shift of the heated volume of gas having lower density than the surrounding colder gas, results 20 in a temperature difference sensed by the two temperature-sensitive elements. Acceleration applied in directions perpendicular to the gas flow also causes shift of the heated volume of gas, but this shift is in a direction which does not significantly change the temperature difference measured at the two temperature-sensitive elements. Therefore the transducer has 25 low sensitivity to acceleration perpendicular to gas flow. In general, in a single sensor, the acceleration-induced output signal is indistinguishable from a flow-induced signal. Sensitivity to acceleration of the considered differential pressure transducers adversely affects the accuracy of the transducers and hence the gas flowmeter exposed to mechanical 30 disturbances such as vibrations, rotation and displacement.

- 5 -

Another problem is also caused by the necessity to detect and process differential pressure signals approximately 1000 times lower than those generated by near-linear GFRs (for example, Fleisch- or Lilly-type tubes in spirometry). During flowmeter operation (for example, spirometry 5 testing), some vibrations or shocks of the device parts, such as the pneumatic hoses connecting the GFR with differential pressure sensor, may occur. Being negligibly small with respect to differential pressure signals generated by linear GFRs, these parasitic signals may nevertheless be significant compared to useful signals generated by nonlinear GFRs. 10 Interference by spurious signals such as these, reduces the accuracy of the flowmeter. Immunity to these vibrations is considered to be an important feature of the flowmeter especially for compact hand-held versions of the instrument. Signal filtering techniques to suppress parasitic signals can be used, as long as they do not violate any standards in the field of 15 application. For example, spirometry standards define a speed of response required to measure flow parameters of the patient's respiration which should be maintained by any spirometer.

A flowmeter containing two nonlinear functional elements, such as the GFR and thermoanemometer-type sensor, has a complex and 20 essentially nonlinear conversion characteristic from flow to output voltage, which must be linearized. To linearize the flowmeter, its calibration curve $F(V)$, which specifies the correspondence between the flow F and the measured voltage V , must be defined. The present invention addresses 25 also linearization of an essentially nonlinear flowmeter, containing a GFR with flow-resistive element generating differential pressure close to the square of the flow.

Contemporary spirometers typically contain analog-to-digital converters (ADC), digitizing analog signals from the transducer for subsequent processing. To provide the required resolution in the wide 30 operating range of almost six orders of magnitude mentioned above, an ADC with resolution higher than 16-18 bits should be used. Meanwhile,

- 6 -

comparatively cheap, simple and widespread 12-bit ADCs are preferable. Therefore the problem of resolving of low flows (in the flowmeter with nonlinear GFR), arises not only from the restricted sensitivity of differential pressure transducers, but also from the limited resolution of the preferred 5 electronic circuitry.

Summary of the Invention

It is an object of the present invention to provide the following solutions:

- Improve effectiveness of the GFR by increasing its (differential pressure)-to-(back pressure) ratio;
- Simplify the shape of the GFR for better reproducibility and easier manufacturing;
- Improve immunity of the flowmeter to vibrations or shocks of the device and its parts, including the thermoanemometer-type differential pressure 15 and flow transducers.
- Improve resolution and hence accuracy of the flowmeter at low flows;
- Accurate linearization of the gas flowmeter.

1. One of the goals of the invention is solved by the new design of the flow-20 resistive element of the GFR. The flow-resistive element is made in the form of an obstacle to gas flow having non-symmetrical shape when viewed along the long axis of the GFR tube. The flow-resistive element is designed to simultaneously obtain low overall back-pressure, and high local differential pressure measured between two points inside the GFR. The 25 local differential pressure is created by placing an obstacle in the GFR, directly between the two points inside the GFR at which the differential pressure is measured, typically, in the case of bi-directional flow measurement, as close as possible to the midpoint of the line connecting these two points.

- 7 -

According to a broad aspect of this feature, there is provided a gas flow receiver comprising a flow tube having a sidewall and guiding flow therethrough while inducing minimal resistance, an upstream sensing tube having an upstream orifice communicating with the flow tube via the

5 sidewall, and a downstream sensing tube having a downstream orifice communicating with the flow tube via the sidewall. The receiver also has a non-symmetrical-flow-inducing diaphragm mounted in the flow tube between the upstream and the downstream orifices, and causing non-symmetrical flow in the flow tube with an accentuated higher pressure near

10 the upstream orifice than would be sensed in a corresponding cross-section of the flow tube and an accentuated lower pressure near the downstream orifice than would be sensed in a corresponding cross-section of the flow tube, the orifices being positioned with respect to the diaphragm so as to sense accentuated pressure substantially without sensing

15 pressure oscillations due to any turbulence induced by the diaphragm.

Preferably, the diaphragm is mounted to the sidewall between the orifices. The diaphragm may be shaped so as to exhibit high drag and generate maximum accentuated pressure for its size. The flow tube may have a smaller cross-section between the orifices and may be similarly

20 tapered on both sides of the small cross-section.

2. To improve immunity to vibrations of the thermoanemometer-type differential pressure transducer, two or more thermoanemometer-type flow-sensitive elements are connected and used such that the parasitic

25 acceleration-induced components of the signals can be separated from the flow-induced components, and cancelled, thus allowing identification of the flow-induced signals.

In general, this can be accomplished by using a plurality of flow-sensitive elements connected in such a way that flow and acceleration act

30 in different directions (angles) at different flow-sensitive elements. Many

different embodiments are possible. For example, two thermoanemometer-type flow-sensitive elements are connected in a specific way, such that the gas flows through each of the elements in opposite directions. The output signals of the two flow-sensitive elements are processed electronically so

5 that the acceleration-induced components of the signals are cancelled, while flow-induced components of the signals are doubled.

Another combination may also include at least one flow-sensitive element through which no gas flows. Being subjected to the applied acceleration, this reference element generates an output signal which is

10 used to cancel the acceleration-induced component of the element through which the gas flows.

According to a broad aspect of this feature, there is provided a gas flow transducer apparatus with immunity to vibration or acceleration, which comprises a plurality of gas flow transducer elements each sensitive to

15 vibration or acceleration in at least one direction and generating an output signal proportional to gas flow and to a perturbation component resulting from the vibration or acceleration. The transducer elements are arranged on a common support and a plurality of gas flow passages leading gas flow from an inlet to an outlet through at least one of the transducer elements.

20 The elements are arranged on the common support and connected to the passages such that at least one of the perturbation component and the gas flow is measured differently by the transducer elements. Circuitry is provided that receives the output signal of each of the transducer elements and outputs a vibration or acceleration immune output signal corresponding

25 to the gas flow with the perturbation component substantially cancelled.

The gas flow passages may cause the gas flow to be equal through the transducer elements, and the gas flow may be split between the transducer elements, or it may pass serially through the transducer elements. Preferably, two transducer elements are provided that are

30 sensitive to vibration or acceleration along only one axis and are arranged

- 9 -

parallel to one another, the gas flow passages being arranged such that the gas flow is in opposite directions through the transducer elements.

Gas flow may be blocked in at least one of the transducer elements, wherein the at least one of the transducer elements measures only the
5 perturbation component.

Preferably, the at least one of the transducer elements communicates with the gas flow such that the at least one of the transducer elements is subjected to a same gas composition and temperature as other ones of the transducer elements.

10 The transducer elements preferably comprise thermoanemometer-type transducers.

3. To enhance flowmeter resolution at low flows, which would otherwise be limited by the quantization noise of ADC, the following signal processing is
15 proposed.

Option 1.

- 3.1) The output analog signal of the differential pressure transducer should have high frequency components at frequencies $f > 1/\Delta t$, where Δt is the ADC sampling rate, where the amplitude of these high-frequency components must exceed one quantization unit of the ADC;
- 20 3.2) If the output analog signal of the differential pressure transducer does not have high frequency components at frequencies $f > 1/\Delta t$ with amplitude exceeding one quantization unit of the ADC, then an artificially-generated oscillating signal, or noise, meeting this criteria should be mixed with the signal prior to digitizing by the ADC;
- 25 3.3) The average output signal voltage is calculated by arithmetic averaging of several samples from the output of the ADC, during a

- 10 -

time $\tau = N \cdot \Delta t$, where $N > 2$, resulting in resolution better than the quantization unit of the ADC;

3.4) The flow corresponding to averaged signal voltage from 3.3) is calculated from the calibration curve of the flowmeter;

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Option 2. The output analog signal of the differential pressure transducer, as specified above in 3.1)-3.2), can be further processed as follows:

3.5) The flow corresponding to the digitized output signal voltage sample is calculated from the calibration curve of the flowmeter;

10 3.6) The averaged flow is calculated during time $\tau = N \cdot \Delta t$, where $N > 2$.

According to a broad aspect of this feature, there is provided a method of estimating a value of an analog signal using an analog-to-digital converter (ADC) with a level of precision greater than a minimum quantization value of the ADC. The method comprises:

15 adding a secondary signal to the analog signal, the secondary signal having a zero DC component, a substantially even and symmetric amplitude distribution and a peak-to-peak amplitude greater than the minimum quantization value;

recording and storing a digital output value of the ADC;

20 averaging the digital output value recorded over a sampling period to obtain an estimated higher precision digital value with a precision greater than a precision of the digital output value.

25 Preferably, the secondary signal is provided by noise generated in amplifier circuitry used to amplify the analog signal, and the analog signal may be a gas flow transducer signal in addition to other types of signal.

Preferably, the sampling period varies as a function of an amplitude of the analog signal, wherein the sampling period is longer for lower amplitude values and is shorter for higher amplitude values.

- 11 -

4. To suppress parasitic signals due to vibrations or shocks of the flowmeter or its parts, without degrading the frequency response of the device, the output analog signal of the differential pressure transducer, conditioned with high-frequency components as specified in 3.1)-3.2), can 5 be processed as follows:

4.1) The whole operating range of the flowmeter is divided into at least 2 (preferably more) non-overlapping sub-ranges. The number of sub-ranges can be theoretically up to the number of quantization units in the ADC. The averaging times can then be different for each sub-
10 range;

4.2) When flow is measured in accord with 3.3), 3.4) or 3.5) above, the averaging times must monotonically decrease from low-flow sub-range(s) to high-flow sub-range(s).

According to a broad aspect of this feature, there is provided a
15 method of filtering a signal comprising the steps of measuring an amplitude of the signal, determining an averaging period τ as a function of the amplitude, wherein τ is longer for lower values of the amplitude and τ is shorter for higher values of the amplitude, and averaging the amplitude over the period to provide a filtered output signal.

20 The function may be a step function. When the amplitude is above a predetermined threshold, the filtered output signal may be the instantaneous value of the amplitude. Preferably, the step of measuring comprises converting an analog gas flow transducer signal to a digital signal providing the amplitude.

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5. The general type of the calibration function, $F(V)$, of the flowmeter containing flow-resistive element generating differential pressure close to the square of flow, is invented:

- 12 -

$$F(V) = \sum_{i=1}^N A_i V^{\frac{i}{\alpha_i}}$$

where N is equal or greater than 3; parameters $\alpha_i > 1$ (preferable values of α_i are close to 2); and A_i are coefficients determined experimentally for a particular flowmeter, to give the best linearization results. For higher

5 accuracy, the whole operating range of the flowmeter is divided into several (at least two) sub-ranges, and a calibration function is found separately for each of the sub-ranges by the same method.

According to a broad aspect of this feature, there is provided a method of processing a transducer output signal that is non-linear with

10 respect to a physical parameter being measured to obtain a calibrated output signal representing the physical parameter on a given scale. The method comprises:

subjecting the transducer to a number of calibrated physical parameter conditions;

15 recording a value of the output under each of the conditions;

obtaining an analytical solution for a non-linear function relating the output value to the physical parameter, the solution being expressed as:

$$F(V) = \sum_{i=1}^N A_i V^{\frac{i}{\alpha_i}}$$

where V is the transducer output signal; N is greater than or equal to 3;

20 parameters A_i are coefficients determined from the recorded values; α_i are real numbers;

determining the calibrated output signal for the transducer output signal using the analytical solution.

Preferably α_i are greater than 1, and may be non-integers.

25 The step of determining may comprise:

- 13 -

calculating a value of the physical parameter for each possible value of the transducer output signal using the analytical solution; and

building a table of the physical parameter values indexed by digital output values;

5 converting the transducer output signal into a digital output value; and

obtaining a value of the calibrated output signal from the table using the digital output value.

The analytical solution may be exact for each of the recorded
10 values, and the analytical function may be divided into subranges.

The transducer output signal may be derived from a gas flow transducer signal having a square transfer function, and the gas flow transducer is preferably a thermoanemometer-type transducer apparatus.

15 Brief Description of the Drawings

The invention will be better understood by way of the following, non-limiting, detailed description of a preferred embodiment and alternate embodiments with reference to the appended drawings, in which:

Fig. 1 is a schematic of the flowmeter containing the Gas Flow
20 Receiver, differential pressure transducer, analog electronic module and ADC module;

Fig. 2 is the Gas Flow Receiver with star-like diaphragm (prior art);

Fig. 3 is the Gas Flow Receiver with the invented non-symmetrical flow-resistive element;

25 Fig. 4 shows the measured back-pressure versus flow for both types of the GFRs;

Fig. 5 shows the measured ratio η of differential pressures generated by non-symmetrical and symmetrical flow resistive elements versus flow;

- 14 -

Fig. 6 shows deviations of experimentally-measured syringe volume from its actual value obtained during "expiration" and "inspiration", at different averaged flow rates for the GFR with symmetrical star-like obstacle;

5 Fig. 7 shows deviations of experimentally-measured syringe volume from its actual value obtained during "expiration" and "inspiration," at different averaged flow rates for the GFR with inverted non-symmetrical flow-resistive element;

Fig. 8 is a schematic side view of the GFRs;

10 Fig. 9 is a schematic front view of the flow resistive element within the GFR tube (viewed along the long axis of the tube);

15 Figs. 10 and 11 show the configuration of the invented differential pressure and flow transducer containing two thermoanemometer-type flow-sensitive elements. The channel for flowing gas connects two elements in series (Fig. 10), or in parallel (Fig. 11);

Fig. 12 depicts a schematic of a single flow-sensitive element with acceleration applied to it;

Fig. 13 shows an example of a more complex configuration involving three flow-sensitive elements connected in a triangle;

20 Fig. 14 shows the configuration of two identically-aligned flow-sensitive elements with flow passing through only one of them;

Fig. 15 shows (a) unfiltered, and (b) filtered output signals of the flowmeter at low flows;

Fig. 16 is a block-diagram of the electronic module of the flowmeter;

25 Figs. 17 and 18 are flow charts describing the invented signal processing;

Fig. 19 shows the reaction of the flowmeter to a flow impulse; and

Fig. 20 shows a calibration curve of the flowmeter.

Description of the Preferred Embodiment

In the preferred embodiment, a gas flow receiver has a non-symmetrical-flow-inducing diaphragm mounted in a flow tube and causes non-symmetrical flow in the flow tube with an accentuated higher pressure 5 near an upstream orifice than would be sensed in a corresponding cross-section of the flow tube and an accentuated lower pressure near a downstream orifice. A gas flowmeter using thermoanemometer-type transducers receiving gas flow from the upstream orifice is made immune to vibration or acceleration, for example, by arranging a pair of the 10 transducers parallel to one another with the gas flow passing serially through them, but in opposite directions. The resulting transducer signals processed to cancel the effect of the vibration or acceleration. The transducer output is amplified by a noisy amplifier which injects a secondary signal prior to digital conversion using an ADC. The digital signal 15 is averaged over a sampling period to obtain a sample having a level of precision greater than a minimum quantization value of the ADC. The sampling period is varied as a function of the transducer's analog signal amplitude, such that the sampling period is longer for lower amplitude values and is shorter for higher amplitude values. The sampling period 20 variation provides signal filtering. Since the flowmeter has a non-linear response, a calibrated output signal representing flow is obtained by recording samples under a number of calibrated flows and obtaining an analytical solution for the non-linear function, using the analytical solution to obtain calibrated values for all sample values, and, in operation, looking up 25 a calibrated value corresponding to a sample value. Having briefly described the features of the preferred embodiment together, the individual features will now be described hereinbelow in greater detail.

The present application describes a variety of inventive features applicable to a gas flowmeter. These features improve the characteristics 30 of the flowmeter. Maximum effectiveness of the improvement can be

reached when the inventions discussed below are implemented jointly and are therefore presented together herein.

5 TUBE FOR CONVERSION OF GAS FLOW TO DIFFERENTIAL PRESSURE

Fig. 1 shows a schematic view of the flowmeter containing GFR 1, differential pressure transducer 2, analog electronic module 3 and ADC module 4. The flow-resistive element 5 of the invented gas flow receiver (GFR) 1 is designed to simultaneously obtain low overall back-pressure, 10 and high local differential pressure measured between two points inside the GFR 1 for bi-directional flow measurement, for example in spirometry. The local differential pressure is created by placing an obstacle 5 in the GFR 1, directly between the two points inside the GFR 1 at which the differential pressure is measured, as close as possible to the midpoint of the line 15 connecting these two points. In some circumstances, it may be desirable for the obstacle or diaphragm to be positioned offset from the midpoint.

To prove the invented idea, two experimental GFRs have been constructed. Each of the star-like symmetrical diaphragm 7 and the invented non-symmetrical diaphragm 5 were placed in the middle of 20 identical tubes 120mm long with input inner diameter of 21mm and inner diameter of 19mm at the center of the tube (Figs. 2 and 3). The shapes of the flow-resistive elements have been chosen so as to generate back pressure lower than 150Pa·s/l (required by ATS standards for spirometry). The six beams of the star-like diaphragm 7 have width of 1mm each. The 25 central spot of the diaphragm has a diameter of 4mm. The non-symmetrical diaphragm 5 has the shape of a circular segment with height of 4mm. The star-like diaphragm 7 has thickness of 1mm while the segment-type diaphragm 5 has a thickness of 0.1-0.2mm.

Each of the GFRs was connected to the same differential pressure 30 transducer 2 and individually calibrated. Back pressure was measured by

- 17 -

an additional pressure sensor. A 3-liter calibration syringe called "SpiroCal" manufactured by Burdick Inc. (Milton, WI, USA), was used to generate gas flows during the experiments. Fig. 4 shows the dependence of back pressure on air flow, for the two GFRs. Fig. 5 depicts the ratio $\eta = \Delta P_1 / \Delta P_2$

5 as function of flow, where ΔP_1 and ΔP_2 are differential pressures generated by the GFRs with the invented non-symmetrical diaphragm 5, and symmetrical star-like diaphragm 7, respectively. The invented GFR generates lower back pressure and higher differential pressure than the GFR with symmetrical diaphragm 7.

10 To check the sensitivity of the two tubes to gas velocity distribution across the cross-section of the tube, the following two-step experiment was performed. In the first step, each tube (after calibration) was connected to the syringe, and gas was "inspired" from the ambient through the tube into the syringe by piston strokes at different flow rates – "inspiration". The

15 inspired volume was measured by integrating flow measurements over time, and compared with the actual volume of the syringe. In the second step, each tube was rotated by 180 degrees, such that its flow direction was reversed, and connected to the syringe with its opposite end, and the same experiments were conducted except with gas being pumped out of

20 the syringe, by "expiration" piston strokes. Thus, the direction of gas flow in the tubes was the same, but the connections, and thus, the gas flow velocity distributions in the flux, were different. In the first step, the GFR input is connected directly to an infinite volume of ambient gas, while in the second step the gas flux entering the GFR is shaped by a 40mm-long

25 connecting tube with inner diameter of 30mm. Deviations (in %) of experimentally measured syringe volume from its actual value, obtained in the regimes "expiration" and "inspiration" at different averaged flows, for the two tested GFRs, are presented in Figs. 6 and 7. The GFR with the star-like diaphragm 7 demonstrated a discrepancy in measured volumes up to

30 8.5% due to changes of its orientation, which confirms its sensitivity to gas velocity distribution across the cross-section of the tube. For the invented

tube, these discrepancies did not exceed 1%, which demonstrates substantially lower sensitivity to gas velocity distribution across the cross-section of the tube.

The invented GFR has a simpler shape than the GFR with 5 symmetrical star-like diaphragm or crest-type flow resistive element. This can simplify its manufacturing and improve reproducibility of the conversion characteristic.

The described embodiment confirms the advantages of the invented solution. Meanwhile, other shapes of non-symmetrical flow-resistive 10 element can be used according to the invention. GFRs containing the invented flow-resistive elements in the form of non-symmetrical circular segments with heights of 3mm and 5mm, have been also tested. Experimental results are shown in Figs. 4 and 5, represented by circular 15 and triangular symbols, respectively. These variations have also demonstrated low sensitivity to gas velocity distribution across the cross-section of the tube.

An increase of the thickness of the circular segment obstacle from 0.2mm to 1-2mm does not cause significant changes in the conversion 20 characteristics of the GFR. Observed deviations of back-pressure and local differential pressure did not exceed 5%.

Figs. 8 and 9 show several possible designs of the GFR, which do not exhaust all possible shapes of the GFRs. The particular choice of GFR should be made to provide optimal adaptation to the given application and manufacturing techniques. In Fig. 8, different cross-sections of flow- 25 resistive element 8, 9, 10 are shown inside the GFR 1. The GFR 1 may also contain tubing 11 attached at a certain angle. Front views of plane diaphragms 12, 13, 14 used as flow-resistive elements are shown in Fig. 9.

In the preferred embodiment, the flow measured is bi-directional. In the case that the flow is in one direction, the positioning of the non-

- 19 -

symmetrical diaphragm may preferably be in a position different from the midpoint between the sensing tube orifices.

5 DIFFERENTIAL PRESSURE AND GAS FLOW TRANSDUCER WITH
IMMUNITY TO VIBRATIONS/ACCELERATION

Figs. 10 and 11 show two possible configurations of the invented transducer, where two flow-sensitive elements 15 are connected in series (Fig. 10), and in parallel (Fig. 11). In both cases, the gas flowing through the channels passes through the flow-sensitive elements in opposite 10 directions. Therefore, the heated volumes of gas 16 near the heaters 17 in both flow-sensitive elements 15 (shown as shaded circles), are also shifted in opposite directions causing inverted output signal components. When acceleration is applied in the direction parallel to gas flow as shown on Fig. 12, heated volumes of gas 16 are shifted in the same direction for both 15 flow-sensitive elements 15 causing increments in output signals which are the same for both sensors. The output signals $V_{sensor1}$ and $V_{sensor2}$ of the two flow-sensitive elements 15 are then processed by electronic circuitry 3, such that one signal is subtracted from the other. The following three equations summarize the situation.

20
$$V_{sensor1} = V_{flow} + V_{acceleration}$$
$$V_{sensor2} = -V_{flow} + V_{acceleration}$$
$$V_{sensor1} - V_{sensor2} = 2 \cdot V_{flow},$$

where V_{flow} and $V_{acceleration}$ are the sensor output voltage components caused by gas flow and applied acceleration, respectively.

25 If the two linear flow-sensitive elements 15 are identical, sensitivity to acceleration of the whole transducer can be reduced theoretically to zero. In practice, the immunity to acceleration may be limited by mismatch of the two sensor elements 15 and calibration of their sensitivities.

30 The choice of schemes presented in Figs. 10 and 11 depends on the particular application. The transducer with two flow-sensitive elements 15

- 20 -

connected in series has flow impedance two times higher than a single element, while the second transducer (Fig. 11) has flow impedance two times lower.

For experimental verification of the invented concept, a prototype of

5 the transducer was assembled on the basis of two AWM2200 mass flow sensors (Honeywell) connected in series by plastic hoses. The performance of the assembled prototype was compared with the performance of a single AWM2200 sensor. The electronic circuitries of the transducers provided the same sensitivity to differential pressure. Then

10 both devices were rotated in the Earth's gravity. The single AWM2200 sensor has sensitivity to acceleration of 14mV/g while the prototype of the invented transducer is completely immune to the same acceleration within the resolution of the electronic circuitry (less than 1mV). Both tested transducers have the same sensitivity to gas flow.

15 The invented configuration of the transducer 2, immune to acceleration, can be realized by a variety of methods. The best results may be obtained by the usage of identical flow-sensitive elements. These flow-sensitive elements may be commercially available sensors as described above or specially designed functional sensing elements.

20 Among other possible configurations, one is shown in Fig. 13, where three flow-sensitive elements are arranged in the same plane and connected in the shape of a triangle. In this case, the output signals of each flow-sensitive element can be written as:

$$V_{sensor1} = V_{flow} + V_{acceleration} \cos(60^\circ - \beta)$$

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$$V_{sensor2} = V_{flow} + V_{acceleration} \cos(60^\circ + \beta)$$
$$V_{sensor3} = -V_{flow} - V_{acceleration} \cos(\beta)$$

where β is the effective angle of the acceleration, as shown in Fig. 13.

This system of three equations with three unknown parameters, V_{flow} , $V_{acceleration}$ and β , can be solved to cancel the influence of the

30 acceleration-induced component of the signal.

- 21 -

Fig. 14 depicts another possible combination of two flow-sensitive elements. The gas passage 18, which is opened to the main gas passageway at one end allows the reference sensor to experience the same gas composition, pressure and temperature, without experiencing the 5 gas flow. When conditions of gas composition, pressure and temperature are constant, sensor 2 may be isolated without using the passage 18. In this case, the following three equations summarize the sensors output signals and the obtaining of the flow signal. The output signals of the sensors are:

10 $V_{sensor1} = V_{flow} + V_{acceleration}$

$$V_{sensor2} = V_{acceleration}$$

$$V_{sensor1} - V_{sensor2} = V_{flow}$$

Processing of the output signals can thus cancel the acceleration-induced component of the signal.

15 The following points should be noted:

In addition to the described acceleration compensation, compensation for variations in temperature, gas composition and ambient pressure also may be implemented in ways typically used in mass-flow controllers. Meanwhile, the invented acceleration suppression is effective 20 independently of the particular embodiment shown in Figs. 10, 11, 13, 14 and independent of the method of possible compensation of gas temperature, gas composition and ambient pressure.

SIGNAL PROCESSING FOR IMPROVEMENT OF FLOWMETER 25 ACCURACY.

The invented method to improve flowmeter resolution at low flows (which would otherwise be limited by quantization noise of the ADC, unless one is ready to use a high-resolution ADC), by special signal processing was experimentally checked with a flowmeter containing a nonlinear GFR 30 1, described above, and mass flow sensor AWM2200, manufactured by

Honeywell Inc. and connected to the GFR 1 by two plastic hoses 6. Sensor excitation and signal amplification was performed by the circuitry recommended by the manufacturer. The severe decrease of the flowmeter sensitivity at low flows results from the near-square-law dependence of 5 differential pressure versus flow generated by the GFR 1. The limited resolution of the ADC 4 restricts minimal detectable flow. At the same time, parasitic vibration-caused signals are large enough to degrade accuracy of the flowmeter at low flows. As an example, Fig. 15a shows the influence of the intentionally generated vibrations of the pneumatic hoses 6. The 10 minimum detectable flow defined by the resolution of the ADC 4 (flow corresponding to +1mV or -1mV, the quantization unit of the ADC) was found to be approximately 50ml/s (without the invented signal processing). In the described experiment, the electronic module contained a typical 12-bit ADC 4 (AD7890-4). The digitized signal, with sampling rate $\Delta t = 2\text{ms}$, 15 was transferred to a personal computer for visualization, storage and processing.

The reasonable useful frequency bandwidth of the electronic module for the detection of variable flows, specified by the ATS standards, need not be greater than 100-150Hz. To artificially increase the high-frequency 20 noise component of the analog output signal in accord with the invention (as specified above in 3.2)), the frequency bandwidth of the electronic module was intentionally increased up to 10kHz. The increased high-frequency noise component of the analog output signal, determined by approximately white noise of the operational amplifiers of the circuitry, had 25 amplitude of approximately $\pm 3\text{mV}$, equivalent to three quantization units of the ADC 4. This added noise is shown in Fig. 15a. A schematic block-diagram of the device is shown in Fig. 16. In the described experimentally-checked embodiment, additional noise was generated inside the analog circuitry module.

Flow charts describing signal processing in the microprocessor-based module are shown in Figs. 17 and 18. To suppress signals due to vibrations of the hoses 6 without degrading of the flowmeter dynamic properties, the following filtering parameters were used. The operating flow 5 range of the flowmeter was divided into four sub-ranges:

$0 \leq \text{flow} \leq 0.5 \text{ l/s}$;

$0.5 \text{ l/s} < \text{flow} \leq 1 \text{ l/s}$;

$1 \text{ l/s} < \text{flow} \leq 2 \text{ l/s}$;

$2 \text{ l/s} < \text{flow} \leq 15 \text{ l/s}$.

10 The averaging time τ was chosen to be 72ms ($N_1=36$) for the first sub-range, 30ms ($N_2=15$) for the second sub-range, 12ms ($N_3=6$) for the third sub-range and 6ms ($N_4=3$) for the fourth sub-range. In accord with the first preferred embodiment (Fig. 17), after the analog voltage output of the transducer is transformed by ADC into digital format, the corresponding 15 flow is found from the calibration curve of the flowmeter. Then flow readings are stored in the buffer in such a way that at least the last N_i readings are in the buffer. The present flow is analyzed to find out which of the four sub-ranges it belongs to. Depending on the result of the analysis, flow is averaged through last N_i readings stored in the buffer, if present flow 20 belongs to sub-range i ($i=1\dots4$).

The effectiveness of presented signal processing is shown in Fig. 15b. The averaging of the signal allowed increase in flow resolution from 50ml/s to approximately 5ml/s. The suppression factor for vibration-generated signals is approximately 7-8.

25 Another possible filtering sequence is shown in Fig. 18. The difference of this signal processing from previous one is the following:
- four sub-ranges are defined in terms of voltage (not flow);
- averaging is done with voltage transformed into digital format;

- 24 -

- resulting flow corresponding to averaged voltage is found from the calibration curve of the flowmeter.

While very important at low flows, the described filtering procedure may be redundant at higher flows because of the steep signal rise

5 proportional to approximately the square of flow. For example, a rise of flow from 50ml/s to 2 l/s results in signal increase by a factor of $1600=40^2$ which is more than one order of magnitude higher than the usual parasitic signals due to vibrations. On the other hand, the high frequency response of the flowmeter is required mainly at high flows (for example, spirometry), which

10 would be degraded by a long averaging time τ . Thus, the usage of several sub-ranges with low averaging times at high flows, maintains satisfactory speed of response at medium and high flows. Fig. 19 shows the reaction of the flowmeter to a flow impulse generated by a "SpiroCal" 3-liter syringe. At high flows, the filtered signal (b) has the same shape as the unfiltered

15 signal (a). Its fall time is estimated to be less than 10ms. The effect of filtering at low flows can be recognized by the effective suppression of the oscillating acoustic signal generated by the collision of the piston with the syringe bottom.

The parameters of this filtering method, i.e. number of flow sub-

20 ranges, averaging times and amplitude of the analog signal noise component, can be chosen to optimize the operation of the flowmeter for a particular application. The parameters of the investigated physical process resulting in this choice are: required frequency response and flow operating range of the flowmeter, and intensity and frequency spectrum of the

25 parasitic signals to be suppressed.

METHOD FOR FLOWMETER LINEARIZATION.

Typically, calibration of the flowmeter involves the following steps:

- measuring of the flowmeter output voltage at several reference flows;

- 25 -

- calculation of an analytical function which fits the actual calibration curve of the flowmeter;
- storage of the analytical function as:
 - a table which gives unambiguous correspondence of all possible 5 ADC readings to flow;
 - parameters of the analytical function which allow calculation of flow for each ADC reading during the flowmeter operation.

Usually, a high precision flow generator is used to calibrate the flowmeter at several reference flows. The number of these reference flows 10 should not exceed 10-20. Otherwise the calibration procedure would be unacceptably long. On the other hand, even a 12-bit ADC which is typically used in flowmeters measures 4096 voltage levels in the operating range of the device. Therefore finding an analytical function which accurately fits the actual calibration curve of the flowmeter and allows determination of flows 15 corresponding to all possible ADC readings, is critically important. Methods of curve fitting are well-known and are not considered here.

The type of analytical function $F(V)$ which gives optimal fitting for the described flowmeter is disclosed:

$$F(V) = \sum_{i=1}^N A_i V^{\frac{i}{\alpha_i}},$$

20 where V is the output voltage of the flowmeter; N is greater than or equal to 3; parameters A_i are coefficients determined experimentally; α_i are real numbers (not necessary integer), typically greater than 1.

For verification of the invented linearization method, a prototype 25 flowmeter was used. The flow meter was based on the GFR 1 described above, containing the 120mm long tube with input inner diameter of 21mm and inner diameter of 19mm at the center of the tube. A planar non-symmetrical diaphragm 5 having the shape of a circular segment with height of 4mm (Fig. 3), was used as a flow-resistive element. This

diaphragm with thickness of 0.2mm was located at the center of the tube, and generated differential pressure close to the square of the flow (square transfer function). Mass flow sensor AWM2200 (Honeywell) was connected to the GFR 1 with two plastic hoses 6 to measure flow-induced differential pressure. The flowmeter also contained a 12-bit ADC AD7890-10 operating in the range $\pm 10V$.

In accordance with the invention, the operating flow range of the flowmeter was divided into two sub-ranges, 0 – 2 l/s and 2 – 15 l/s. The coefficients A_i of the calibration curve $F(V)$ were found for $N=5$ and $\alpha_i=2$.
 10 Two functions defined separately for the two sub-ranges are graphed in Fig. 20. After calibration, the calibration curve was stored in form of the table in a computer file.

For checking of the flowmeter accuracy, its GFR was connected to the "SpiroCal" 3-liter calibration syringe. Then, air was pumped in and out 15 of the syringe with different flow rates by piston strokes. The expired and inspired air volumes were measured by the flowmeter and compared with the actual volume of the syringe. Deviations of these two volumes (in %) shown in Fig. 7, do not exceed 2%. This confirms that the accuracy of the flowmeter is within 2% or better, exceeding the requirements specified by 20 the ATS standards for spirometry.

In practice, the choice of the parameters N and α_i may differ from those used in the example presented herein, depending on the applications. For example, the linearization procedure was also successfully tested with $N=6$, although the algorithm of finding of 25 coefficients A_i was more complicated.

The parameters α_i can be chosen so as to give better fitting of the calculated calibration curve with actual flow response of the flowmeter. At low flows, the dominant contribution is given by the first element of the sum: $F(V) \approx A_1 V^{\frac{1}{\alpha_1}}$. Transforming this equation, one obtains $V \approx bF^{\alpha_1}$. In

- 27 -

this case, the parameter α_1 defines conversion from flow to output voltage at low flows, which mainly depends on the construction of the GFR 1. Usually, the GFR 1 with diaphragm-type flow-resistive elements 5 generates differential pressure which varies near to the square of flow 5 (square transfer function). For these types of GFRs 1, $\alpha_1=2$ gives a reasonable approximation of the calibration curve. Nevertheless some deviations of the parameter α_1 as well as parameters α_i ($1 < i < N$) from the value of 2 are also included in the invented linearization method.

Depending on the accuracy requirements and flow operating range, 10 the number of sub-ranges may also vary from one to some number greater than two. This choice depends on the particular application.